Baseline Experimental Results on the Effect of Oil Temperature on Shrouded Meshed Spur Gear Windage Power Loss

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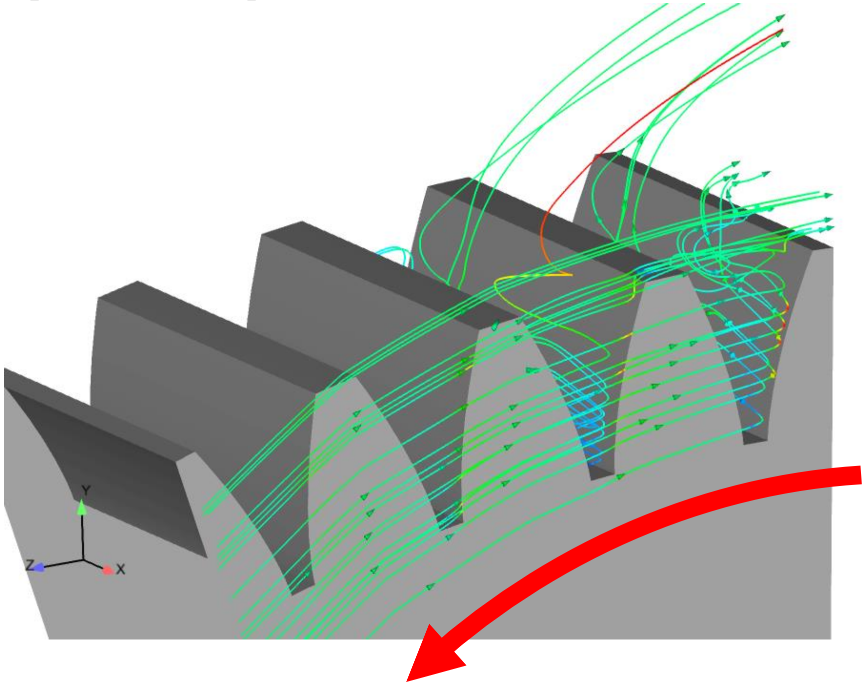
Windage power loss (WPL)

- Drag on gear tooth in transmitting load.
- Viscous drag on gear faces
- Air/Oil impingement on tooth surface (inertia effects)
- Significant at greater than 10,000 ft./min. (51 m/s)
- Gearbox efficiency losses
- Reduced rotorcraft performance (i.e. payload, range)



Ref:
Hill, Matthew J., et al. "CFD analysis of gear windage losses: Validation and parametric aerodynamic studies." Journal of Fluids Engineering 133.3 (2011): 031103.

Shrouded Spur Gear WPL Work

- (1984) Dawson: "Windage Loss in Larger High-Speed Gears"
  - single spur gears, air
  - reduction in WPL with axial and radial shrouding
- (1998) Lord: "An Experimental Investigation of Geometric and Oil Flow Effects on Gear Windage and Meshing Losses"
  - single and meshed spur gears, shrouding, air/oil
  - decrease in WPL with increasing oil temp., increase in WPL with increasing oil flow
- (2011) Combined Analysis & Experimental Validation
  - single spur gear analyses, shrouding
  - Hill: "CFD Analysis of Gear Windage Losses…."
  - Handschuh: "Initial Expts. of High-Speed Drive Sys. Windage Losses"
- (2017) Delgado and Hurrell: "Experimental Investigation of Shrouding on Meshed Spur Gear Windage Power Loss"
  - 7x to 12x increase in WPL for meshed spur gears compared to single spur gears
  - Explore WPL sensitivity to oil flow rate and oil temperature

Focus of this work

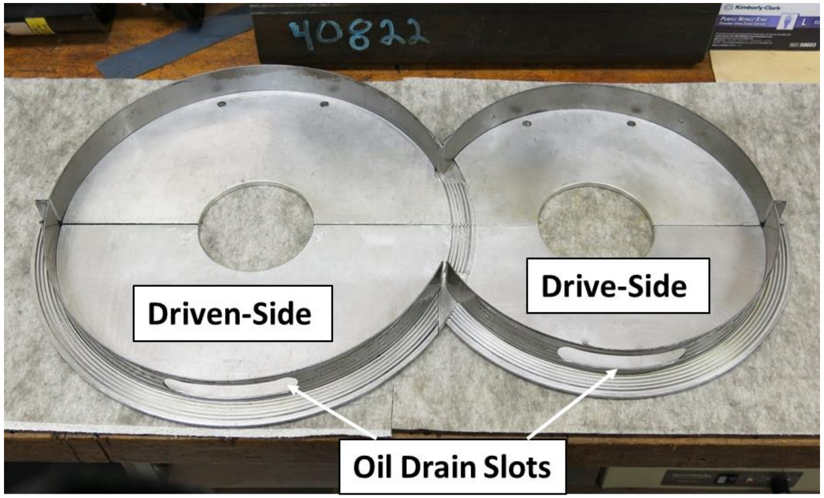
- Obtain WPL experimental on meshed spur gears
  - Oil inlet temperatures: 100°F (38°C), 125°F (52°C), 160°F (71°C), 180°F (82°C)
  - Constant oil pressure
  - 4 shroud configurations
- Compare with literature
  - Single vs Meshed
  - Unshrouded vs Shrouded
- Identify WPL trends, if any
- Outline additional research

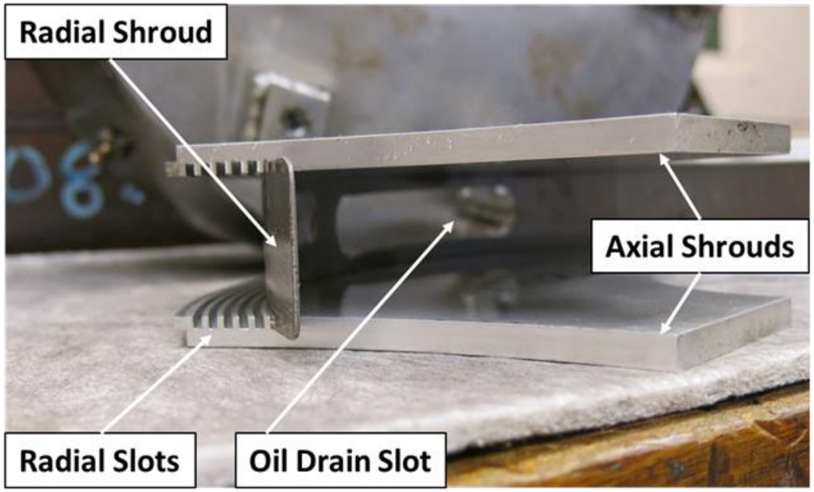
Gear Information

Gear Parameter	Drive-side	Driven-side
Number of teeth	44	52
Pitch / module, 1/in. (mm)	4 (6.35)	
Face Width in. (mm)	1.12 (28.4)	1.12 (28.4)
Pitch Diameter, in. (mm)	11.0 (279.4)	13.0 (330.2)
Pressure Angle, deg.	25	
Outside Diameter, in. (mm)	11.49 (291.85)	13.49 (342.65)
Material	Steel-SAE 5150H	

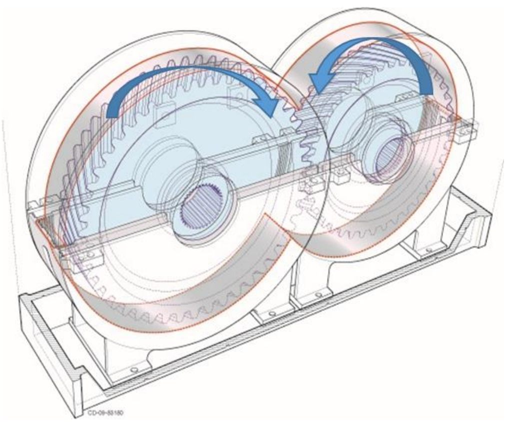
Shroud Information

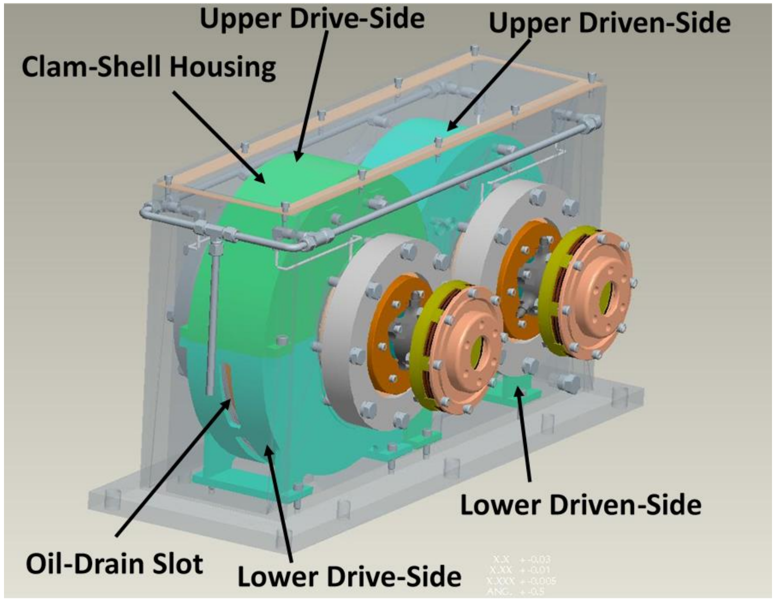
Shroud Config.	Axial Clearance	Radial Clearance	
	Per side [inches] (mm)	Drive [inches] (mm)	Driven [inches] (mm)
(U) Unshrouded w/o clam-shell housing	2.25 (57.15)	2.5 (63.5)	1.0 (25.4)
(CS) Unshrouded w/ clam-shell housing	1.5 (38.1)	0.82 (20.83)	0.82 (20.83)
(C36) shrouded	1.2 (30.5)	0.66 (16.76)	0.66 (16.76)
(C1) shrouded	0.039 (1.00)	0.039 (1.00)	0.039 (1.00)





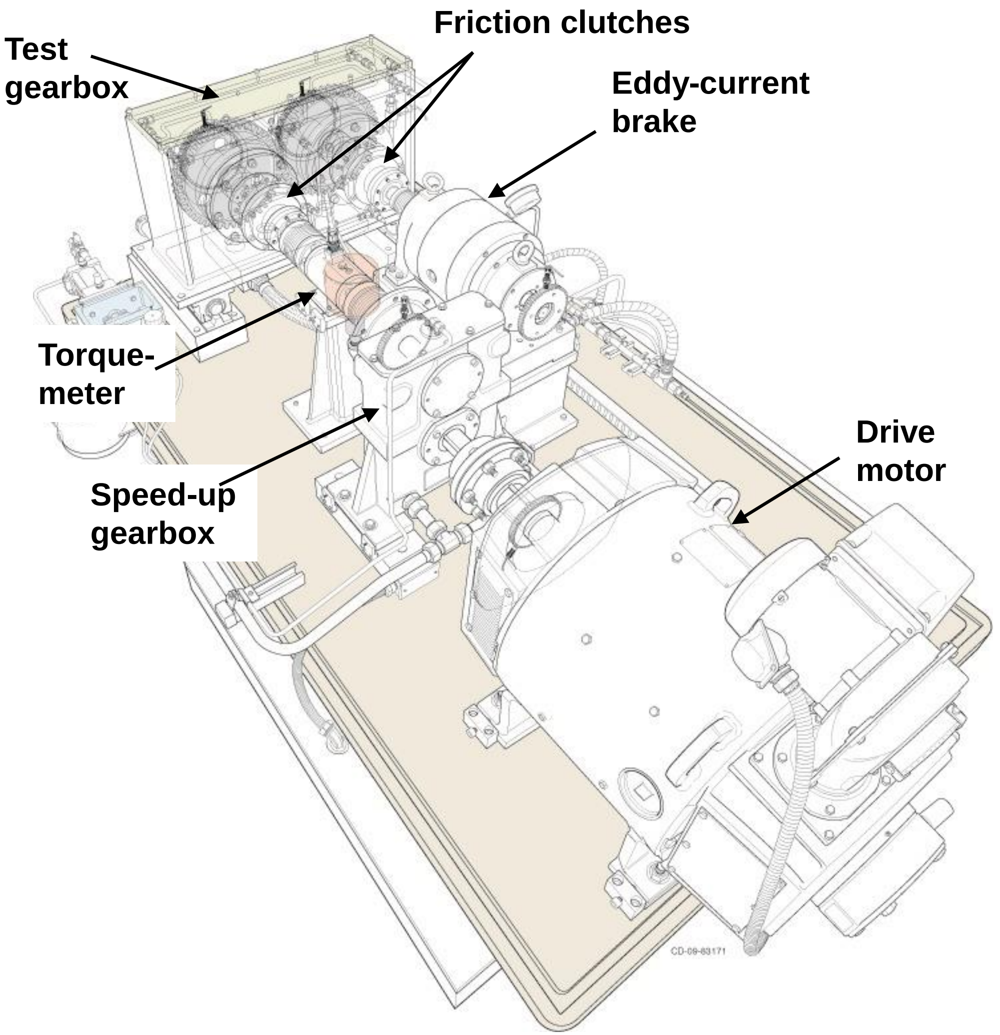
Continued - Shrouding





NASA WPL Test Rig

- dc motor:
  150 hp (112 kW)
- speed-up gearbox:
  1:5.17 ratio
- Eddy-current brake:
  73.8 ft.-lb. (100 N-m) at
  2865 rpm (300 rad./sec.)
- torque-meter:
  2,000 in-lbs (226 N-m)
- Into-mesh lubrication
- Measurements
  shaft speed
  gear fling-off temperature
  gear mesh oil flow
  oil inlet/exit temperature



WPL Test

- Spin-down at 10,000 rpm (1047 rad/s)

  (i.e. disengage drive motor, clutches, dynamometer)

  10,000 rpm (1047 rad/s) in 2000 rpm increments every 100 seconds

  Record speed vs time

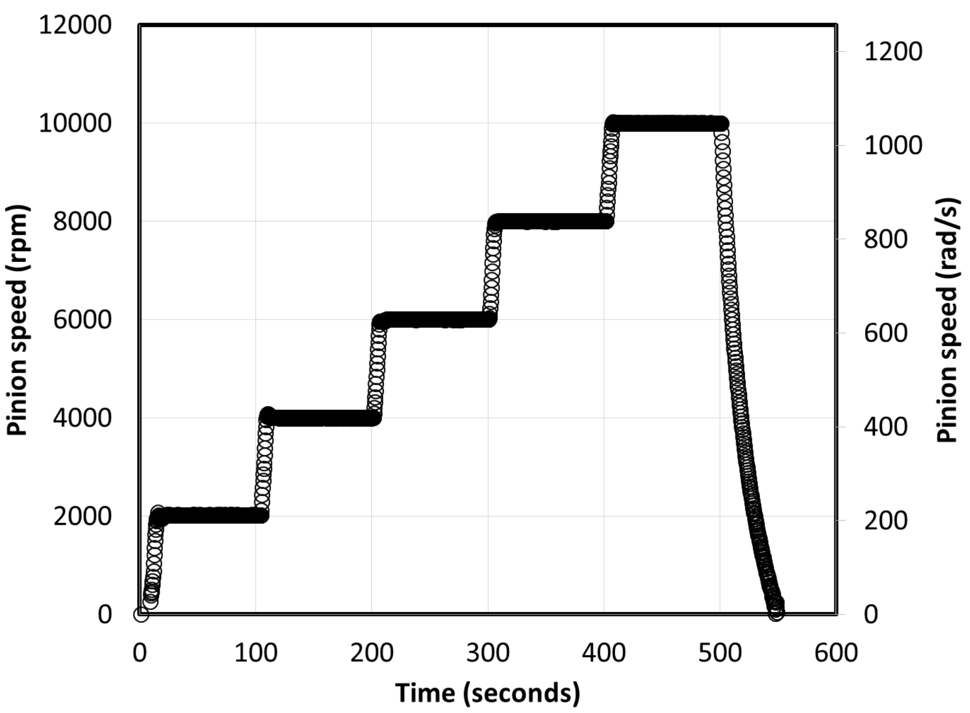
  Repeat 2x for 3 cycles total.

- Oil In:

  100°F (38°C), 125°F (52°C), 160°F (71°C), 180°F (82°C)

- Shroud Config

  U, CS, C36, C1



WPL Calculation

- $\mathbf{WPL = P_{total} - P_{gear\ mesh} - P_{driveline\ losses}}$
- $\mathbf{P_{total}} = (\tau_{system}[\text{ft-lbf}] \times N[\text{rpm}]) \div 5252$

  $\tau_{system} = I_{system} \times \alpha_{system}$

  I_{system} (equivalent inertia for meshed spur gears)

  α_{system} via experiment
- $\mathbf{P_{gear\ mesh}}$ (estimated via NASA TP 1622, minimal, 1%)
- $\mathbf{P_{driveline\ losses}} = (\tau_{driveline}[\text{ft-lbf}] \times N[\text{rpm}]) \div 5252$

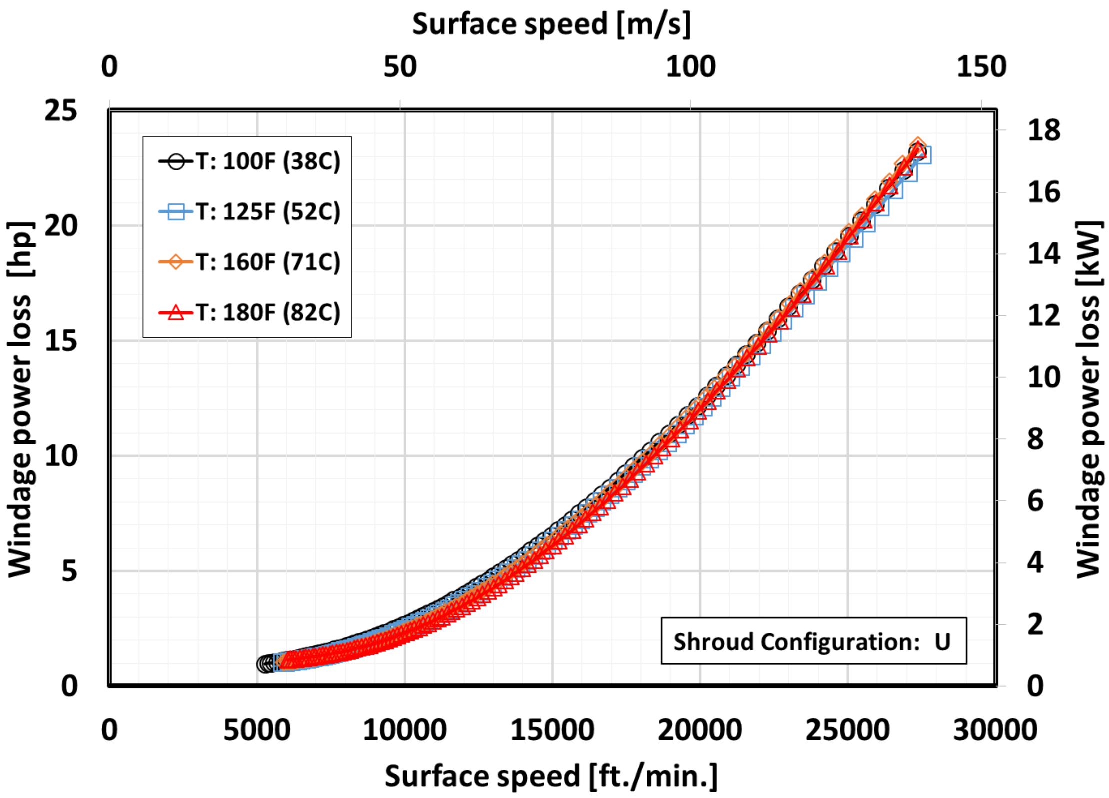
  $\tau_{driveline} = I_{driveline} \times \alpha_{driveline}$

  $I_{driveline}$ (curved rail method by Genta)

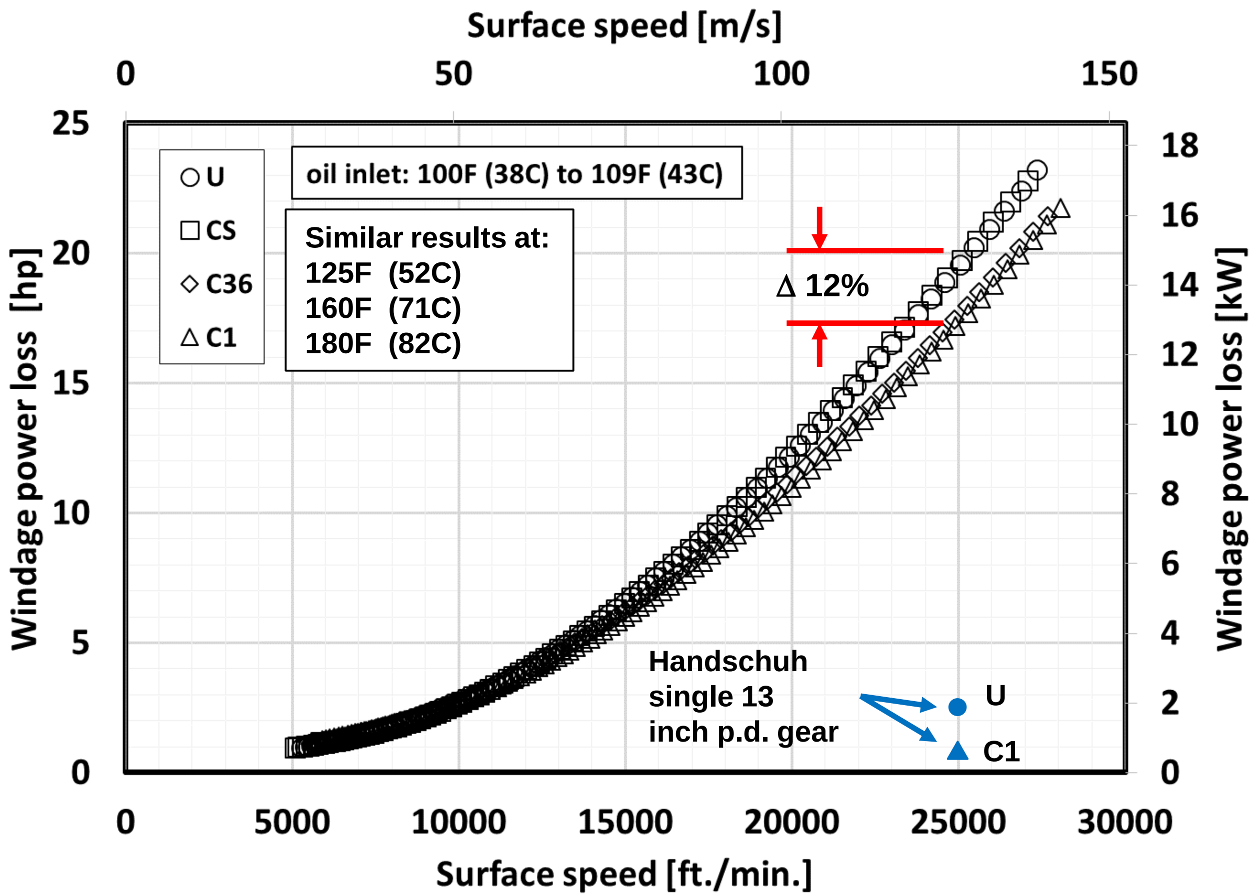
  $\alpha_{driveline}$ via experiment

WPL variation with increased oil temp.

- WPL unchanged with increased oil inlet temperature
- oil flow increased with temperature:
  0.73 gpm (2.76 lpm),
  0.90 gpm (3.41 lpm),
  0.97 gpm (3.67 lpm),
  1.05 gpm (3.97 lpm)
- Indicative of WPL sensitivity to oil flow
- WPL unchanged for CS, C36, C1 configs.

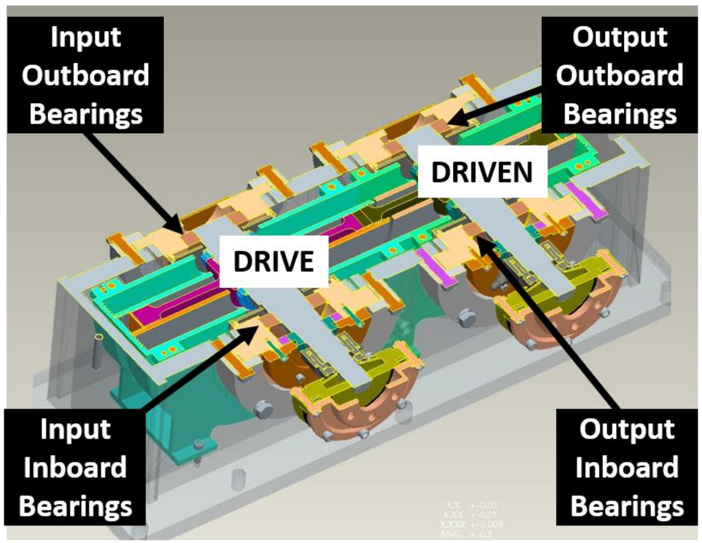


WPL variation w/shroud configuration

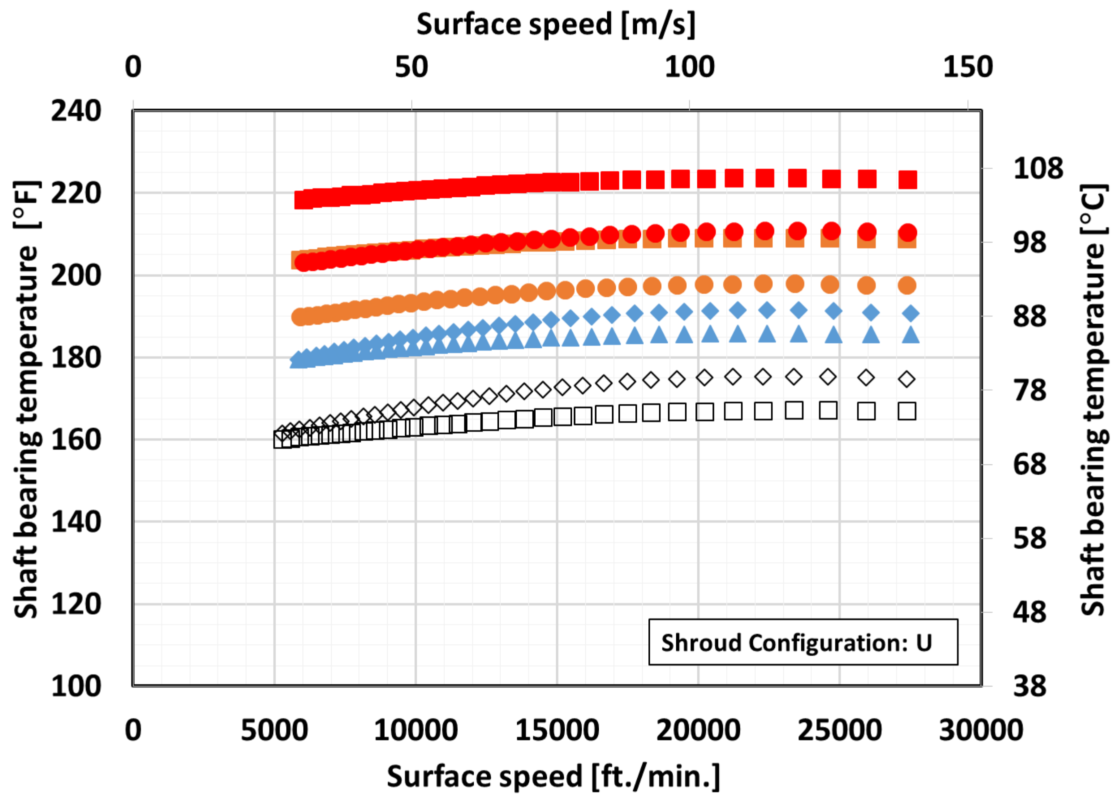


- Increase in WPL of ~10x (single vs. meshed)
- More than double
- Possible WPL insensitivity to shrouding (i.e. C36 vs C1) at surface speeds tested

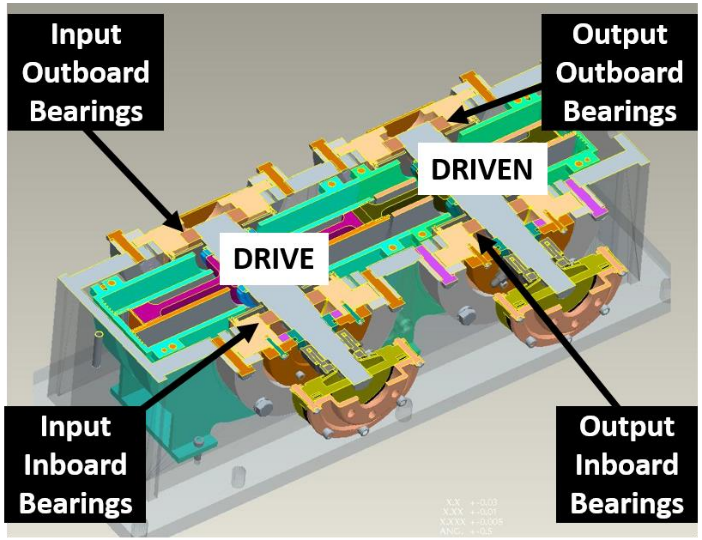
Brg. temp. variation: U configuration



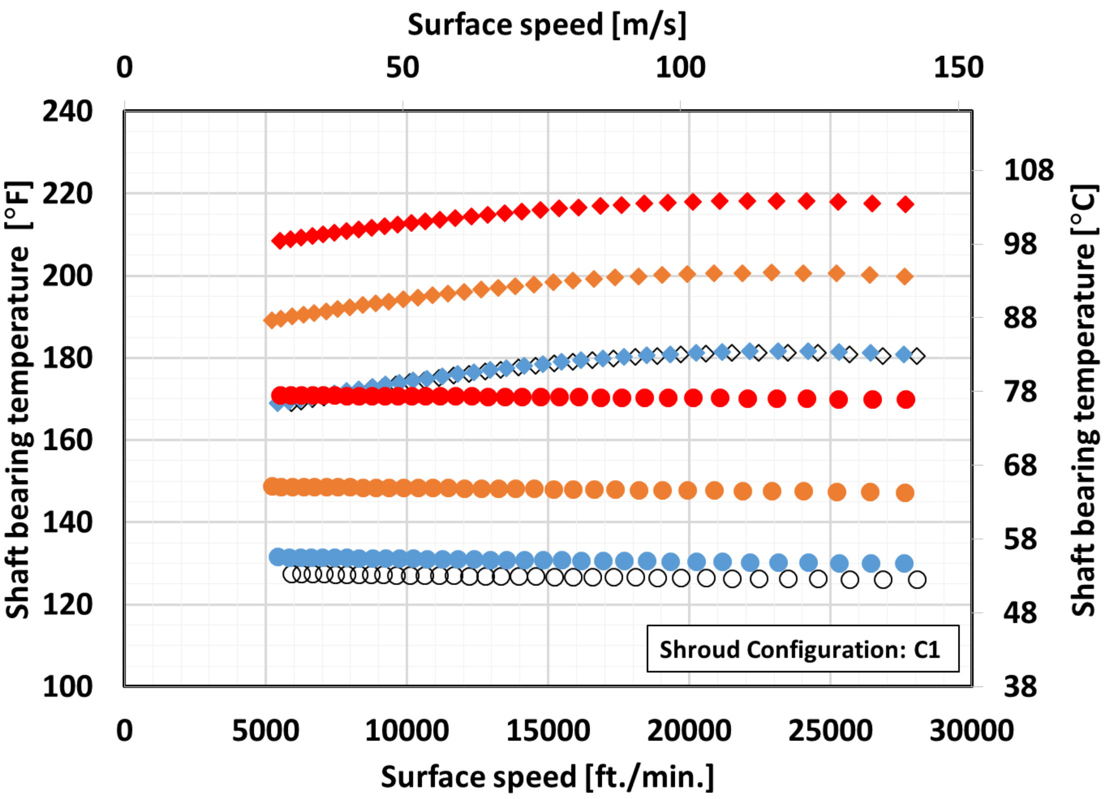
Input Inboard	Input Outboard	Output Inboard	Output Outboard
○ T100:IPIB	□ T100:IPOB	◇ T100:OPIB	△ T100:OPOB
● T125:IPIB	■ T125:IPOB	◆ T125:OPIB	▲ T125:OPOB
● T160:IPIB	■ T160:IPOB	◆ T160:OPIB	▲ T160:OPOB
● T180:IPIB	■ T180:IPOB	◆ T180:OPIB	▲ T180:OPOB



Brg. temp. variation: C1 configuration

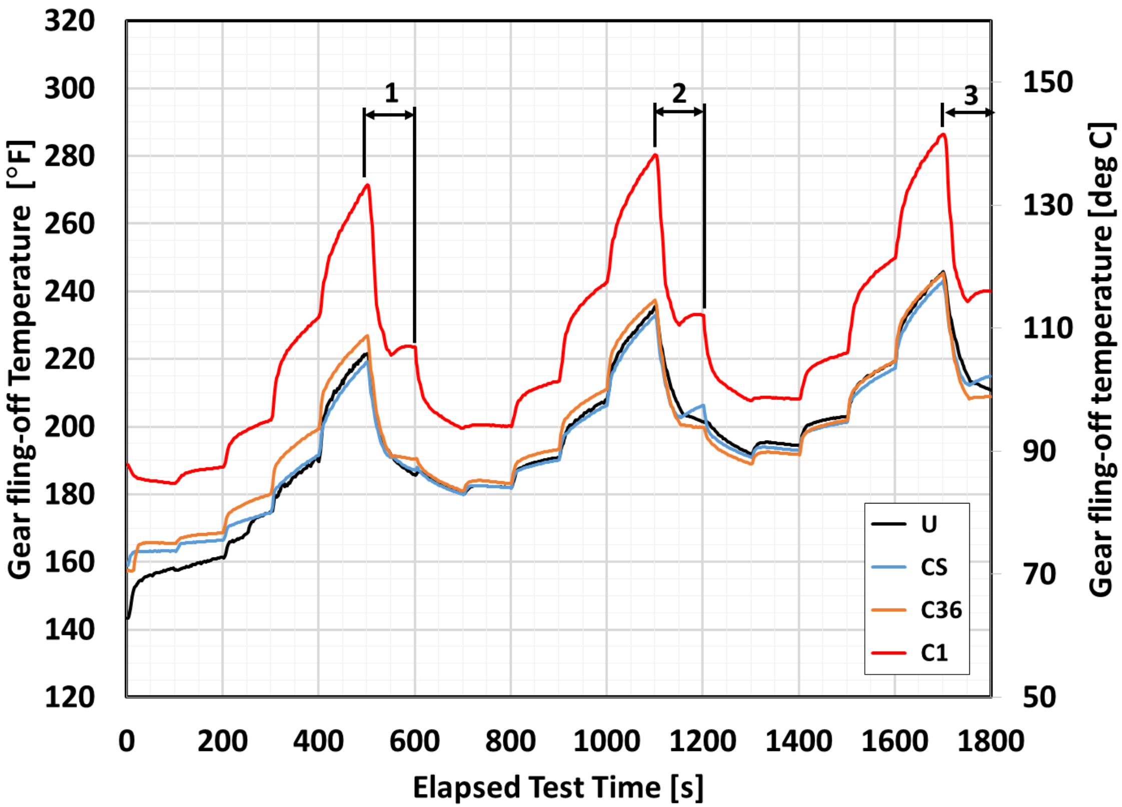


Input Inboard		Input Outboard		Output Inboard		Output Outboard	
○	T100:IPIB	□	T100:IPOB	◇	T100:OPIB	△	T100:OPOB
●	T125:IPIB	■	T125:IPOB	◆	T125:OPIB	▲	T125:OPOB
●	T160:IPIB	■	T160:IPOB	◆	T160:OPIB	▲	T160:OPOB
●	T180:IPIB	■	T180:IPOB	◆	T180:OPIB	▲	T180:OPOB



Gear fling-off (GFO) temp. variation

- GFO highest with C1 config.
- 40-50°F (20-30°C) difference at 28,000 ft./min. (142 m/s)
- Nearly identical GFO temps. for C36, CS, and U configurations
- Close clearance shrouds may increase local heating to gear



Summary Points

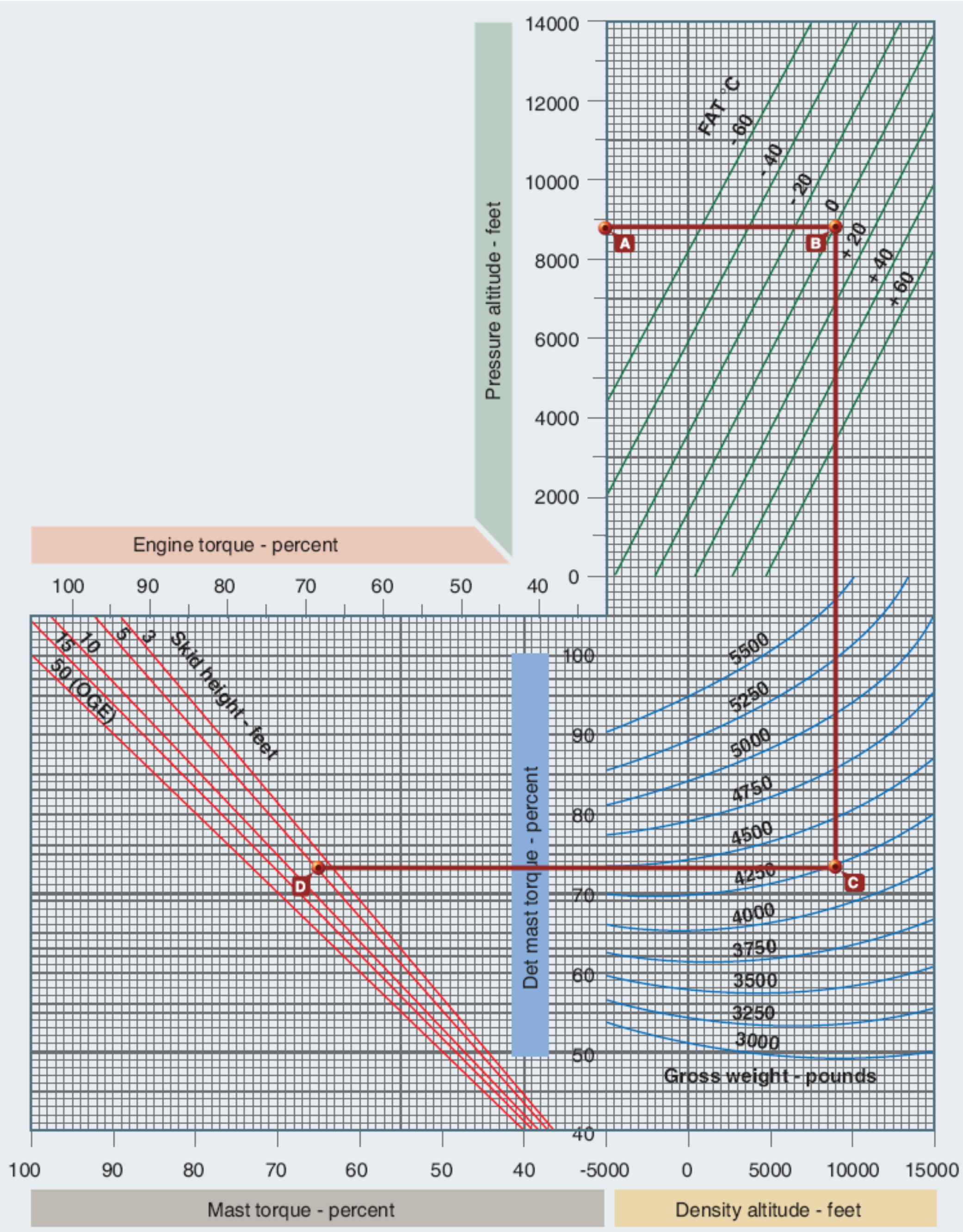
- At controlled oil pressure at tested oil inlet temperatures:
  - WPL data were identical for the U and CS shroud configurations.
  - WPL data were identical for the C36 and C1 shroud configurations
  - WPL data (C36 & C1) less than (U & CS) shroud configurations.
  - Potential insensitivity of WPL to shrouding (C36 vs C1) for surface speeds tested
- Shroud effectiveness may be reduced if oil temperatures and oil flows are not controlled.
- Shrouding appears to limit conductive and convective heat transfer to the surrounding structure
  - could potentially be used to limit localized heating to the vicinity of the rotating gears.
  - Increased heating to gear (i.e. GFO results) needs to be accounted for
- Estimates of power savings for optimal rotorcraft shrouding should always be stated, or qualified, for a given temperature and lube flow rate. The study presented herein highlights the importance of these parameters on the effectiveness of a given shroud configuration in reducing gearbox windage losses.

Acknowledgements

- NASA Revolutionary Vertical Lift Technology Project
- Robert F. Handschuh
- Sig Lauge

  HX5 Sierra, Technical Test Support

APPENDIX



- Helicopter Performance Chart
- Ref: FAA Helicopter Flying Handbook, Chapter 7.
- Torque required for cruise or level flight, Figure 7.3